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FINAL REPORT

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Limits   to   Predictability   and   Nonlinear   Scaling   in   the   Atmosphere

ONR, N00014-92-J-4068

LONG-TERM GOALS:

The long-range aim of this work was to improve our understanding of the atmosphere through the development of new methods for forecasting and for extracting information from raw time series data.

SCIENTIFIC OBJECTIVES:

The specific aim of this project was to develop and refine nonlinear forecast methods as tools to analyze atmospheric field observations with a view toward the following: (1) to diagnose the underlying dynamic mechanisms driving barometric time series; (2) to determine the effectiveness of nonlinear predictive methods in forecasting atmospheric phenomena; (3) to document and better understand the scale dependence of predictability in atmospheric data.

Both the long-term goal and scientific objectives have been satisfied, as described below.

TECHNICAL ACCOMPLISHMENTS

1) Data procurement:
 From BMRC, Melbourne, we obtained daily time series of station barometric pressures for 38 sites around Australia.   In addition, we obtained three years of daily ECMWF forecasts for Sydney and Perth. These data were used to demonstrate how the methods developed by this project (described below) can significantly improve existing ECMWF forecasts.

2) Methods Development:

i) Developed the method of *residual-delay maps* (RDMs) to measure the degree of nonlinearity in a time series. This method identifies and extracts the functional form of low-dimensional nonlinearity from raw station data (see figure 1). It effectively allows one to empirically deduce the nonlinear component of an equation of motion. We have shown how the RDM can lead to marked improvements in local forecasts based on the ECMWF output (see below). A residual-delay map is generated by plotting the residuals (binned) from a linear AR(3) model against the barometric pressure from the previous day.

ii) Adapted the method of *anisotropic variances* as a simple corroborative method to measure the degree of nonlinearity in a time series. We found that when raw pressures at time t are plotted against pressures at t+1 the anisotropy of variances could be used to characterize the nongaussianity (associated with nonlinearity) of the time series. This is a simple yet effective test to refute the null hypothesis of linear dynamics.

SCIENTIFIC RESULTS:

(i) Using the method of residual delay maps (RDM), we uncovered a very strong and distinctive nonlinear signature in the data for temperate stations. As shown in figure 1, the graph of the binned residual against the lagged barometric pressure has a distinct V-shape at the temperate stations. This quadratic nonlinearity was found to be fully stationary on the inter annual time-scale, and present in all seasons.

(ii) A latitudinal gradient in atmospheric nonlinearity was empirically demonstrated (figure 2). The tropical sites are essentially linear (no structure in the RDM and isotropic variances), while the temperate sites are decidedly nonlinear (a clear V-structure in the RDM and anisotropic variances). This empirical finding supports the prevailing view about the importance of nonlinearity in models for the temperate region.

(iii) One of the compelling reasons for adopting nonlinear time series methods is the possibility that some of the complexity (unexplained variance) in the time series originates from the nonlinear interaction of a few variables, as opposed to the more conventional view that such unexplained variance reflects the action of many variables (high dimensional effects). The stronger

nonlinearity in the temperate regions may explain the apparent noisiness observed in temperate barometric pressure series.

iv) We uncovered evidence to explain the mechanism for the V-structure seen in the temperate data. We showed that the V-structure arises from the asymmetry in time scales of high pressure regimes (persistent) versus low pressure regimes (more ephemeral). This was a very surprising result and supports the hypothesis that atmospheric phenomena can be partitioned into linear and nonlinear components.

(v) We found that the ECMWF model does not reproduce the degree of nonlinearity (from the above mechanism) that is observed in the station data (figure3).

(vi) We found that RDMs applied to ECMWF forecasts for Sydney can reduce average out-of-sample forecast error for extreme climatic events by more than an order of magnitude (from ~2.8hPa to ~0.25 hPa) (figure3).

SCIENTIFIC IMPACT:

i) We demonstrated that barometric pressure in the temperate zone has a distinct nonlinear component, and that this low-dimensional nonlinearity can be extracted from time series data. This is probably the clearest empirical documentation, based on observed time series for the existence of low dimensional nonlinear dynamics in the atmosphere to date. It is also the first study to actually extract the functional form of nonlinearity from any natural time series (after Crutchfield and McNamarra 1987, for model time series).

ii) The mechanism uncovered to explain the V-structure (the asymmetry in time scales of high pressure regimes (persistent) versus low pressure regimes (ephemeral)) has several profound implications.

a) First, insofar as the ECMWF output is concerned, it identifies a source of error which has not been properly modeled in the current state-of-the-art numerical forecasting model. It provides a means for correcting this shortcoming, in the form of a statistical correction term. This is similar to MOS, however, here there is a mechanism for the effect. I have been told by Lenny Smith (Oxford/Reddding) that this correction will soon be implemented

for ECMWF.

b) It provides a general understanding of the effect of spatial scale (grain) on model output, and a general method to significantly improve local forecasts from spatially averaged models such as ECMWF. Thus, until a more expensive fine-grained satellite monitoring and numerical modeling system is in place, this correction, is a reasonable and very inexpensive stop-gap.

c) It supports the hypothesis that atmospheric phenomena can be partitioned into linear and nonlinear components.

iii) The RDM applied to ECMWF output greatly improved out-of-sample forecasts (obtained an order of magnitude reduction in mean forecast error during extreme climatic events at Sydney). Again, as we are told is soon to be implemented, this could be applied in operational forecasts in the form of a statistical correction term (similar to MOS, however, with a mechanism for the effect).

Finding a practical way of reducing systematic forecast error by more than an order of magnitude is seen to be one of the more significant contributions of this project. That this is being implemented in various locations speaks for itself.

TRANSITIONS:

i) Extend the analysis of RDMs to temperature time series.

ii) See whether binned residuals against lagged pressures will produce functions having the same geometry on other time scales. That is, does the V-shaped function which was observed for the daily scale repeat on longer time scales? Or is there a systematic change?

PUBLICATIONS:

B (i) Hastings H. and G. Sugihara 1993 Fractals: A Users Guide for the Natural Sciences. Oxford University Press. 237 pages. (**4th** printing)   (book)

B (ii) Translation of (i) above into German (Birkhauser 1995).   (book)

(iii) Yamazaki, H. , G. Sugihara, G.J. Kirkpatrick and D. Kamykowski 1993. Is the photosynthetic process nonlinear? Journal of Plankton Research, 15:1297-1308.

(iv) Sugihara, G. 1994 Nonlinear forecasting for the classification of natural time series. Phil. Trans. Royal Society of London Series A., No. 1688, 348: 477-495. (invited address).

(v) Sugihara, G. 1994 Prediction as a criterion for classifying natural time series. World Scientific. H. Tong ed.

(vi) Sugihara, G. and A. Hobday 1995. One thousand words = one millipicture. TREE, 10(2): 89-90.

(vii) Dixon, P., A. Hobday and G. Sugihara 1995. Review of fractals in science. Jour. Math. Biol. 57 (6): 939-941.

(viii) Hobday A. 1995. Body size variation in an intertidal limpet: the influence of tidal height, wave exposure and migratory behavior. Jour. Exp. Mar. Biol Eco

(ix) Sugihara G. and L. Bersier 1996. A correspondence between two classical notions of community structure. Rev. Suisse Zool. 102: 855 .

(x) Casdagli, M. C. 1997. Recurrence plots revisited. Physica 108D, volume 108:12-44

(xi) Casdagli, M.C., 1997. Characterizing nonlinearity in weather and epilepsy data: a personal view. in Nonlinear Dynamics and Time Series, Eds. C.Cutler and D. Kaplan, Fields Institute Communications 11, American Mathematical Society.

(xii) Sugihara G., W. Allan, D. Sobel, and K. Allan 1997. Nonlinear control of heart rate variability in human infants. Proc. Natl. Acad. Sci. 93: 2608-2613.

(xiii) Hobday, A., K. Herbinson, and J. McGowan. 1998. Decadal scale stability in a Southern California fish assemblage. (submitted to Ecology).

(xiv) Bersier L. and G. Sugihara. 1997 Scaling regions for food web properties .

Proc. Natl. Acad. Sci., 94: 1247-1251.

(xv)   Bersier, L.F., and G. Sugihara. 1997 Species abundance patterns: the problem of testing stochastic models. JAE: 66: 769-774.

(xvi) Sugihara, G., L.F. Bersier and K. Schoenley. 1997. The effects of taxonomic and trophic aggregation on food web properties. Ocelogia 112:272-284.

(xvii) Bersier L.   The dangers of using small webs to investigate scale invariance in food web properties, Oikos. -

(xviii) Sugihara, G. 1995. From out of the blue.   NATURE   378: 559-560.

(xix) Segundo, P., G. Sugihara, M. Stiber, P. Dixon (In Press) Neurosciences.

(xx) Dixon, P, Milicich M., and G. Sugihara 1999. A new understanding of episodic fluctuations in larval supply. Science (in review).

(xxi) Sugihara G., M. Casdagli, E. Habjan, D. Hess, G. Holland, P. Dixon 1999. Residual delay maps unveil global patterns of atmospheric nonlinearity and produce improved local forecasts. PNAS (provisionally accepted, in review).

ABSTRACTS:
(i) Sugihara, 1995. Extracting and exploiting nonlinearity from atmospheric time series. SIAM.

(ii) Bersier, LF and G. Sugihara, 1996. Scale invariance versus size dependence. Rev. Suisse 103: 799.

RESEARCH PAPERS IN PROGRESS:
(i) Casdagli M., M. Palis and G. Sugihara. Characterizing nonlinearity in weather records: a comparative study. (draft for Physica D).

(ii) Hess D., G. Holland, G. Sugihara, M. Casdagli, Analysis of atmospheric - nonlinearity from field observations (draft for Jour. Atmos. Sci.).

STUDENTS and POSTDOCS Trained during this grant (N=12):

2 Undergraduate trainees/programmers: R. Penner (Latin American), V. Wong (Chinese).

4 Graduate Students (as major advisor): Paul Dixon, Alistair Hobday, Antonio Beumord (Brazilian), James Lerczak.

4 Graduate Students (as doctoral committee member).

2 Post Doctoral Fellows: Louis Bersier (supported by Swiss National Science Foundation), Frank Courchamp (supported by French govt.).

PATENTS:

none.

SPECIAL INVITED LECTURES:

1) Royal Society of London (1994)

2) Colorado State University (1994)

3) Princeton University (1994)

4) Lovelace Institutes, NM (1994)

5) University of Wisconsin (1995)

6) SIAM symposium on Chaos (1995)

7) Merrill Lynch Inc. HK. (1994, 1995)

8) EGS meeting, Hamburg (1995)

9) Deutsche Bank, London (1995)

10) Columbia University (1996)

10) INTECOL, Florence, Italy (1998)

11) Isaac Newton Institute, Cambridge (1998)

SERVICE ON COMMITTEES:

1) Inamori Foundation

2) Nominator for Kyoto Prize

3) Chancellor's Sexual Harassment Arbitration Committee

4) Scientific Advisor for Merrill Lynch Asia Pacific

5) Scientific Advisor for Deutsche Bank

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Subject: N00014-92-J-4068, George Sugihara

Dear Sir/Madam:

Enclosed is the annual progress report for the reference grant "Limits to Predictability and Nonlinear Scaling in the Atmosphere." Thank you for the interest in and support of our programs.

Sincerely,

Nancy Wilson
Manager, Contracts and Grants, SIO

Enclosure